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THERMAL ANALYSIS OF BUILDINGS - CONFIGURATION PERTURBATIONS AND OBSERVED CLIMATE INTERFACE

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ABSTRACT

Results are presented that indicate a proportional relationship between building thermal loads for varying configuration parameters. Through the use of numerous building energy simulations using both the DOE-2.1 and BLAST energy analysis computer programs, it is shown that the relationship is independent of climatic location and covers a broad spectrum of those variables that influence a building's energy use. The theoretical justification associated with such a phenomenon is treated using a multiple regression-derived algebraic expression that clearly establishes the linear independence of a building's heat gain/loss components. Procedures are defined for the simplification of future parametric studies of the thermal analysis of buildings using a methodology that incorporates the observations reported herein.

INTRODUCTION

Various groups of the Applied Science Divison at Lawrence Berkeley Laboratory have been involved in a series of building energy studies that have as their goal a better understanding of the thermal load contributions of a building's configuration components. Interests cover a variety of buildings including single-family residential and multi-family apartment dwellings, as well as commercial office structures. Components studied have been exterior envelope constuction, window properties, internal heat gain and infiltration characteristics, and floor type. The approach taken in these analyses has been one that involves definition of a parametric set bounding the particular variables of interest and the subsequent creation of integrated data bases using hour-by-hour building energy analysis simulation programs such as DOE-2.1 (Lawrence Berkeley Laboratory and Los Alamos Scientific Laboratory, 1981) and BLAST (Hittle, 1979).

In addition to the primary goal mentioned above, each of these studies has also had as a specific requirement the development of simplified methodologies and/or analysis tools that permit the evaluation of energy conservation measures. The techniques employed for such end products have relied on the use of regression analysis to define algebraic expressions that are used to predict energy usage quantities.

Recently, a task was defined that had as its objective the development of a procedure that would reduce the number of required parametric computer runs in creating and/or expanding a data base. Such a task was deemed necessary to minimize the cost of performing annual building energy simulations. Work reported by the Energy Analysis Program (1984) of the Applied Science Division provided the starting point for this investigation primarily because of the availability of a comprehensive data base constructed over the course of several years. The data base was formed from DOE-2.1A computer simulations for five prototype residential buildings (one-story, two-story, split-level, middle unit townhouse, and end unit townhouse) using a climate base of 45 weather locations. Table 1 presents relevant dimension of each of the prototypes. Configuration parameters varied were floor type (slab, basement, crawl), wall, roof, and floor insulation, glass conductance, and infiltration levels. The specific floor type simulated for each prototype was based on survey data that determined the most prevalent foundation type in new home construction at each location. Each parametric set was run for approximately 22 locations.

The basic objective was to expand, in as accurate a manner as possible, the size of this data base so that data would subsequentely exist for all five prototypes, three floor types, and all 45 weather locations. On the surface, such a task does not seem unreasonable considering the size of the initial data set and the fact that one would expect to use various simplifying assumptions well accepted within the building design community. However, after beginning the investigation, it became apparent that such assumptions would not be necessary because of an implicit relationship that existed among configuration parameters, regardless of climate input. This report documents this relationship and defines the climate interface that is apparent between building configurations.

DISCUSSION

A portion of the Energy Analysis Program (1984) data base consisted of simulation results for building variations as outlined on Table 2. These characteristics represent perturbations to the slab-on-grade prototype. Comparable parametrics were also defined for the basement and crawl space configurations. All prototypes modeled consisted of wood frame construction with wall framing corresponding to wood studs 2 in (5.1 cm) x 4 in (10.2 cm) on 16 in (40.6 cm) centers which occupied 25% of the wall area for insulation levels less than R=19 (3.34) and 2 in (5.1 cm) x 6 in (15.2 cm) studs on 24 in (61.0 cm) centers for insulation levels equal to or greater than R=19 (3.34). Ceiling and roof stud values corresponded to the latter for all insulation levels and occupied

10% of the area. Because of space limitations, results in this report are only presented for the single story ranch, slab-on-grade configuration. However, the trends and conclusions are valid for all the prototypes. In addition, data from three other parametric studies are also discussed. These studies yielded similar results and are seen as verification of the characteristics established through the analysis of the Energy Analysis Program (1984) work.

Figures 1 and 2 present the DOE-2.1A heating and cooling thermal load values for 22 weather locations for various alternate configurations (annotated on Table 1) compared to a selected base case model [Roof R=19 (3.340), Wall R=11 (1.94), Floor R=5 (.88), double pane glass, infiltration 0.7 air-changes/hr]. The alternate configurations correspond to changing glass conductance, wall and roof conductance, and infiltration level. Immediately obvious on both figures and the primary reason for this report is the proportional nature of the change in load values regardless of geographic location. Essentially a linear relationship exists between the base case load and the alternate configuration loads as follows:

$$Q_{base} = s \cdot Q_{alt} + t \qquad (1)$$

Thus, if a base case value is known for a specific location, the alternate value is readily definable. This fact is prevalent on both figures with perhaps the heating load being somewhat more linear. The surprising nature of this development led to an investigation of several other parametric studies to establish consistancy.

Table 3 shows heating load correlations coefficients resulting from a least squares fit among the configurations shown on Table 2 for the 22 weather locations. The R^2 values are very close to 1.0 for perturbations that do not involve a major configuration change (primarily occurring diagonally). As one proceeds vertically down or horizontally across (right to left), the R^2 values decrease. This is because larger variations exist between the configurations being compared. Such tables were generated for all the prototypes in the Energy Analysis Program (1984) study and each yielded the same conclusive verification of the observed phenonenon.

Further substantiation was provided by three other independently accomplished studies reported by Carroll et al. (1984), Sullivan et al. (1984), and Turiel et al. (1984). In the Carroll work, which was done by the Solar Program at LBL, the BLAST energy analysis program was used for the purpose of characterizing the thermal mass effects of the envelope of a single-family ranch style house. The four zone (living, kitchen, bedroom, attic) 1200 ft^2 (111.5 m^2) structure is similar to the Hastings (1977) ranch house. Hypothetical external walls covering a range of thermal parameters (thickness, conductivity, density, specific heat, insulation level and placement) provided the primary configuration perturbations. In addition, BLAST simulations were also made for typical frame, masonry, and massless walls at the same value of resistance. Also studied were the effects of thermostat setpoint position and night setback. Six weather locations were selected for analysis under the assumption that the resultant input excitations of temperature, solar radiation, and humidity would adequately bound expected variations throughout the continental U.S.

Heating and cooling loads on Figs. 3 and 4 show the variation from a base case condition [Thk=4 in (9.14 cm), Cond=.5 Btu/hr·ft^2°F (8.64 W/m^2°C, Dens=90 lbs/ft^3 (1440 kg/m^3), SH=.29 Btu/lb°F (1.22 KJ/kg°C)] for varying wall properties for the six locations. As was the case with the DOE-2.1A results, a proportional relationship is again apparent. Heating in Denver appears to be the only condition that is somewhat offset from the lines drawn through the other points. Very interesting results are shown on Figs. 5 an 6 for the base case frame wall versus the masonry and massless walls. The effects of varying thermostat setpoints and night setback are also presented. Again, the results are linear; however, the incremental differences between the masonry and massless walls are nearly constant with geographic location for both heating and cooling. The same is true for the setpoint and setback variation.

Results from Sullivan et al. (1984) are shown on Figs. 7 and 8. This work was undertaken by the Windows Group at LBL using the same ranch style prototype as in the Energy Analysis Program (1984) study. Its purpose was the analysis of fenestration systems through definition of a comprehensive parametric set bounding those items that affect the energy performance of windows, namely: glass conductance, shading coefficient, window size, external and internal shading, and night insulation. Also parameterized to establish component linear independence were internal heat gains, infiltration, and natural ventilation levels. Heating and cooling energies for six alternate fenestration systems are shown on the two figures for five weather locations. In each case a well defined linear relationship exist.

Figures 8 and 9 present results from Turiel's et al. (1984) work on low rise multi-family housing. The prototype analyzed was a two-story building consisting of six 1200 ft^2 (111.5 m^2) apartments. A parametric set similar to the Energy Analysis Program (1984) work (Table 2) was used in creating the data base; however, a smaller number of geographic locations provided the climate variation. The heating and cooling loads shown are average values for the four end units. Similar data was generated for the two middle units. This averaging procedure seems to cause a deterioration of the correlations, as compared to the other studies, when the configuration perturbations involve multiple changes. For example, in comparing Figure 1 and 9, it is seen that as the heating load, for the alternate configurations, decreases because of increased roof and floor insulation, the multi-family results yield a least squares fit that is not as good as the single story ranch. However, the observed proportionality is still apparent.

THEORETICAL CONSIDERATIONS

The studies reported in Johnson et al. (1983) and Sullivan et al. (1984) detailed the use of multiple regression procedures to generate simplified algebraic expressions relating building configuration parameters to the heating and cooling thermal load and/or energy use. Although different building models were used in each analysis, it was shown that a very convenient and compact equation form could be used to accurately predict load or energy. The equation presented below contains the major components contributing to building thermal loads, namely: envelope conductance, solar gains, internal gains, and infiltration.

$$Q_{ij} = \alpha_i C_j + \beta_i S_j + \gamma_i L_j + \delta_i I_j \qquad (2)$$

where

$\alpha, \beta, \gamma, \delta$ = regression coefficients
C = envelope conductance, $U \cdot A$ ($W/^oC$)
S = solar aperature, $SC \cdot A$ (m^2)
L = internal heat gain saturation level (W/m^2)
I = infiltration level (air-changes/hour)
i = geographic location
j = configuration

The regression coefficients represent the climate dependent effect as well as containing conversion factors to insure proper units. Each of the other terms is related to a particular configuration variable. This expression does not contain all load producing items; for example, natural ventilation could be an additional term. However, those items generally deemed necessary for adequate building energy analysis studies are included. Also, the solar gain term ($\beta \cdot S$) has been simplified by neglecting a non-linear quadratic effect. The incremental configuration changes of concern in this study makes this assumption a valid one.

The convenient separation of variables provided by (2) permits an analysis of the influence of each component as well as providing a method of showing under what conditions, the (Q) values of two configurations are linearly related and climate independent. It is easily seen from the nature of this basic expression that the change in a component of (Q) is proportional to the change in a particular configuration variable. However, the linearity to be dealt with is the total heating or cooling load or energy which can be expressed as:

$$\frac{(Q_{b2} - Q_{a2})}{(Q_{b1} - Q_{a1})} = \frac{(Q_{c2} - Q_{a2})}{(Q_{c1} - Q_{a1})} = \frac{(Q_{c2} - Q_{b2})}{(Q_{c1} - Q_{b1})} \qquad (3)$$

where a, b, and c refer to specific weather locations and 1 and 2 to different configurations. This form is used rather than a direct ratio, for example (Q_{b2}/Q_{b1}), since the intercept does not necessarily go through the origin. For equation (3) to be true, the variables α, β, γ, and δ must be related to a specific weather parameter (X_i) in the following fashion:

$$\phi_i = m_\phi \cdot X_i + k_\phi \qquad (4)$$

where (ϕ) represents the regression coefficient and (m) and (k) are slope and intercept values that define the functional dependence on the climate variable (X_i). This statement implies that each coefficient or those which dominate be linearly related to the same weather parameter.

Such a condition is easily seen when one considers the heating requirement. For example, envelope conduction and infiltration, which are both temperature driven, are usually the largest components of the heating load; thus, heating degree hours can be representative of (X_i). Actually, the solar and internal gain terms also correlate with heating degree days, but not in as linear a fashion as the conduction and infiltration, Johnson et al. (1983). The cooling load is somewhat more complicated than heating because of the influence of solar radiation and humidity as well as temperature. Huang (1985) has shown, however, that the cooling load can be linearily related to cooling degree hours that are calculated considering not only outside air temperature but also humidity ratio. Additional work remains to be accomplished in this area both at the total load and component level. The requirement that the form of equation (4) yields the proportion of (3) justifies the search for a weather parameter giving such a result.

Another area that warrants continued investigation is the study of the thermal loads resulting from the stepwise progression from one configuration to another through many intermediate ones. Such a situation was briefly treated by Cleary et al. (1982). This situation arises when the two configurations being compared are significantly different and thus would not be expected to yield the linear relationship being discussed. The intermediate configurations, however, because of the incremental nature of the changes involved, could be related in such a manner. The following expression demonstates how the loads of two disparate configurations at the same location can be related to each other.

$$Q_{a1} = s_n \cdot Q_{an} + t_n \tag{5}$$

where

$$s_n = \prod_{i=1}^{n-1} s_i \quad \text{and} \quad t_n = \sum_{i=2}^{n-1} t_i \cdot \prod_{j=1}^{i-1} s_j + t_1 \tag{6}$$

The subscript (n) is set to one value higher than the number of intermediate configurations being stepped through.

CONCLUSIONS AND RECOMMENDATIONS

The results discussed in this document have implications in regards to future parametric studies involving the thermal analysis of buildings. Understanding the performance of different building parameters in varying geographic locations is greatly simplified through definition of a procedure utilizing the linearity reported herein. It can be tentatively stated that incremental thermal load/energy results can be obtained for any location for an alternate configuration provided the performance of a base case configuration has been defined for all locations interested in and at least two locations have been used to define the changes due to the alternate variations.

Table 4 shows the steps that would be taken to reduce the number of simulations from [NC•NP] to [NC+(2•NP-2)] where (NC) is the number of climate locations and (NP) the number of configuration parametrics. This represents a reduction of [(NC-2)•(NP-1)] computer runs. As an example, consider the case where (NC=45) and (NP=17). The number of required runs would be (765) without the simplifications described herein. Using the procedures outlined on Table 4, changes this number to (77); a net reduction of (688). Such a dramatic change would significatly alter the computer costs associated with performing parametric energy analysis studies. If costs are not of concern, one could greatly increase the number of weather locations or size of the parametric set and achieve a more comprehensive data base for the same original cost.

The figure used in this paper to show the proportional nature of the thermal loads is in itself a very useful tool for comparing configuration options. By creating a grid, as shown on Figure 11, that shows the fractional relationship between the base case configuration values and the alternate configuration values, an indication of the thermal load differences can be indicated (the data corresponds to that presented on Figure 1). What is particularly appealing, of course, is that the presentation covers a wide spectrum of geographic locations.

Certain tasks remain to be accomplished as follows:

Continued investigation of the theoretical considerations and specific definition of the weather variables (particularly those associated with cooling) that justify the linearity as defined in the paper.

With the exception of the results presented on Figures 7 and 8 (Sullivan et al., 1984), all the data relates to residential thermal loads and not energy. Additional work should be done to insure that at the energy level the proportions are still valid. The authors' feeling, based on regression results carried out in the Sullivan et al. (1984) study, is that the thermal load and energy are lineary related in themselves which implies the existance of a multiplier to the load curve presented herein.

The limits of the stepwise progression mentioned in the discussion should be thoroughly defined. This would entail a more rigorous analysis of the present data bases and possibly creation of other parametric studies so that a broader cross section of prototypes can be covered. Also of importance, in this regard, is the examination of commercial building parametric studies. The data from the modular approach used by Johnson et al. (1984) indicates similar relationships to those reported in this paper, however, a more thorough review is recommended.

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TABLE 1 - ENERGY ANALYSIS PROGRAM (1984) RESIDENTIAL PROTOTYPE DIMENSIONS

Building Type	Floor Area $m^2 (ft^2)$	Window Area $m^2 (ft^2)$	Dimensions m (ft)
One-story	143.1 (1540)	14.3 (154)	8.53x16.76x2.44 (28x55x8)
Two-story	208.1 (2240)	20.8 (224)	8.53x12.19x4.88 (28x40x16)
Split-level	176.88 (1904)	19.51 (210)	8.53X14.63X4.88 (28X48X16)
Mid-townhouse	111.48 (1200)	13.38 (144)	6.10x9.14x4.88 (20x30x16)
End-townhouse	111.48 (1200)	13.38 (144)	6.10x9.14x4.88 (20x30x16)

TABLE 2 - ENERGY ANALYSIS PROGRAM (1984) PARAMETRIC SET ALL PROTOTYPES, SLAB-ON-GRADE

Parametric Identifier		Roof Insulation $m^{2o}C/W$ $(hr \cdot ft^{2o}F/Btu)$	Wall Insulation $m^{2o}C/W$ $(hr \cdot ft^{2o}F/Btu)$	Floor Insulation $m^{2o}C/W$ $(hr \cdot ft^{2o}F/Btu)$	Number Panes	Infiltration air-changes/hr
A01		0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	1	0.7
B01		1.94 (11.)	0.0 (0.0)	0.0 (0.0)	1	0.7
C02		1.94 (11.)	1.94 (11.)	0.0 (0.0)	1	0.7
D01		3.34 (19.)	1.94 (11.)	0.0 (0.0)	1	0.7
E01	*	3.34 (19.)	1.94 (11.)	.09 (5.0)	1	0.7
F02	**	3.34 (19.)	1.94 (11.)	.09 (5.0)	2	0.7
G05	*	3.34 (19.)	3.34 (19.)	.09 (5.0)	2	0.7
G01		5.28 (30.)	1.94 (11.)	.09 (5.0)	2	0.7
H04		5.28 (30.)	3.34 (19.)	.09 (5.0)	2	0.7
I07	*	5.28 (30.)	3.34 (19.)	.09 (5.0)	3	0.7
I06		6.69 (38.)	3.34 (19.)	.09 (5.0)	2	0.7
J06		6.59 (38.)	3.34 (19.)	.09 (5.0)	3	0.7
K03		5.28 (30.)	3.34 (19.)	1.76 (10.)	3	0.7
K01		6.69 (38.)	3.34 (19.)	1.76 (10.)	2	0.7
L04		6.69 (38.)	3.34 (19.)	1.76 (10.)	3	0.7
M03		6.69 (38.)	4.75 (27.)	1.76 (10.)	3	0.7
H54	*	5.28 (30.)	3.34 (19.)	.09 (5.0)	2	0.4

** = Base Configuration
 * = Alternate Configurations

TABLE 3 - ENERGY ANALYSIS PROGRAM (1984) HEATING LOAD CORRELATION COEFFICIENTS FOR PARAMETRIC OPTIONS OF THE ONE-STORY SLAB-ON-GRADE CONFIGURATION

Option	A01	B01	C02	D01	E01	F02	G05	G01	H04	I07
B01	0.9989									
C02	0.9973	0.9995								
D01	0.9967	0.9994	0.9999							
E01	0.9948	0.9984	0.9990	0.9998						
F02	0.9920	0.9963	0.9969	0.9984	0.9994					
G05	0.9870	0.9922	0.9952	0.9960	0.9980	0.9998				
G01	0.9902	0.9951	0.9957	0.9977	0.9989	0.9999	1.0000			
H04	0.9873	0.9930	0.9934	0.9963	0.9979	0.9994	0.9998	0.9998		
I07	0.9854	0.9915	0.9915	0.9952	0.9970	0.9990	0.9994	0.9995	0.9999	
I06	0.9824	0.9887	0.9925	0.9936	0.9963	0.9988	0.9996	0.9995	1.0000	0.9999
J06	0.9794	0.9861	0.9904	0.9915	0.9946	0.9979	0.9991	0.9988	0.9997	1.0000
K03	0.9835	0.9901	0.9895	0.9941	0.9962	0.9984	0.9989	0.9991	0.9997	0.9999
K01	0.9800	0.9867	0.9908	0.9919	0.9952	0.9982	0.9992	0.9990	0.9998	0.9999
L04	0.9763	0.9836	0.9882	0.9895	0.9931	0.9969	0.9984	0.9980	0.9992	0.9997
M03	0.9724	0.9802	0.9854	0.9868	0.9909	0.9953	0.9972	0.9967	0.9984	0.9991
H54	0.9741	0.9828	0.9810	0.9884	0.9910	0.9941	0.9936	0.9954	0.9969	0.9976

Option	I06	J06	K03	K01	L04	M03	H54
J06	0.9998						
K03	0.9997	1.0000					
K01	0.9999	0.9999	0.9999				
L04	0.9995	0.9999	1.0000	0.9998			
M03	0.9988	0.9995	0.9996	0.9993	0.9998		
H54	0.9958	0.9967	0.9979	0.9963	0.9971	0.9976	

TABLE 4 - PROCEDURE FOR DETERMINING BUILDING THERMAL LOAD/ENERGY USE

Define base case building

Obtain base case thermal loads/energy results for all weather locations of interest

Define alternate building configuration parametric set

Obtain thermal load/energy results for the parametric set for extreme weather locations to establish relationship between base case and the alternate configurations

For any other location, use the base case value and the established relationship between the base case and the alternate configuration value to define the thermal load/energy

FIGURE 1 Residential Heating Load Comparison for Various Configurations and Geographic Locations(TRY) Using DOE–2.1A, Ranch Style House, Slab–on–Grade, One Zone 143 m^2 Effect of Envelope Conductance and Infiltration

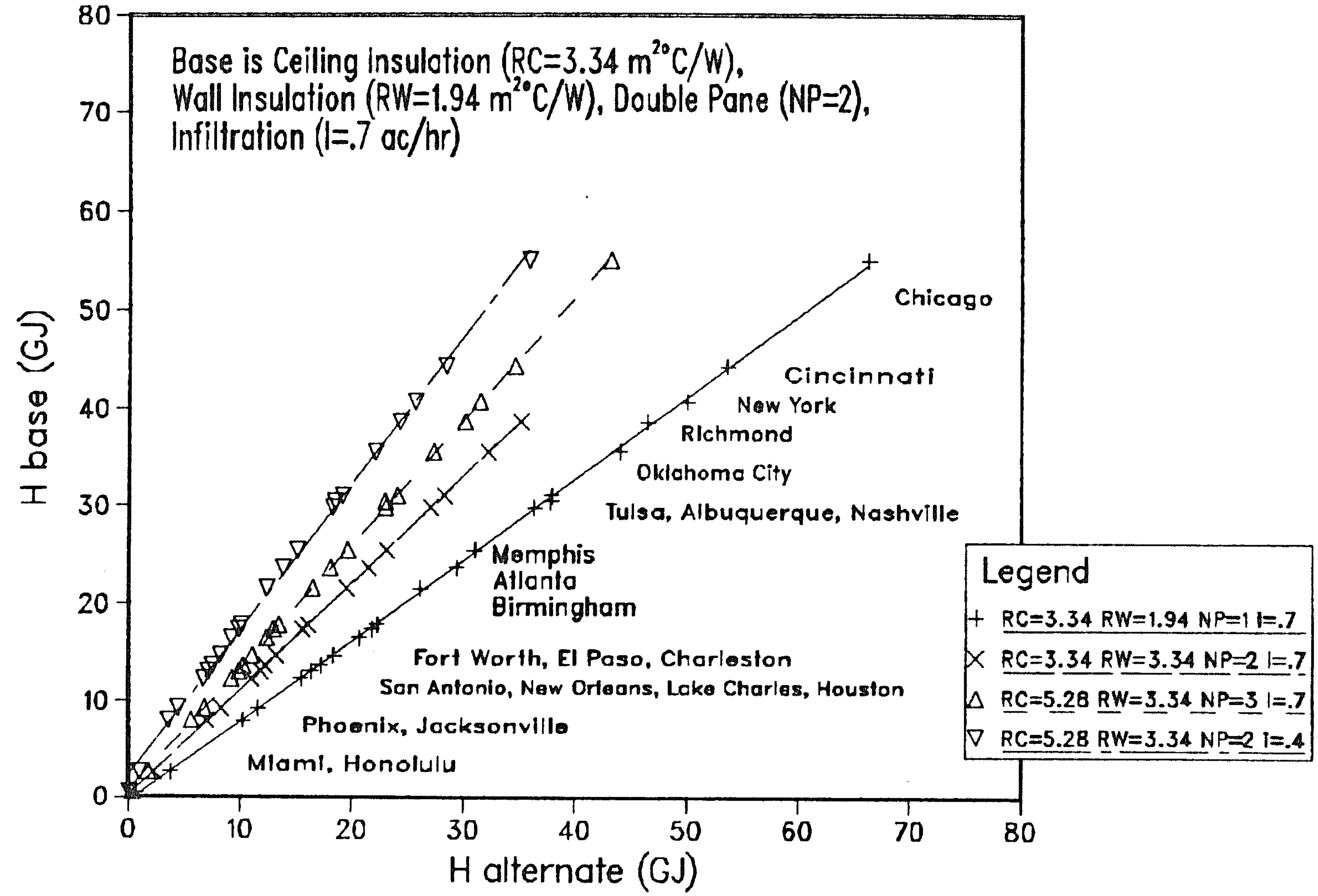

FIGURE 2 Residential Cooling Load Comparison for Various Configurations and Geographic Locations(TRY) Using DOE–2.1A, Ranch Style House, Slab–on–Grade, One Zone 143 m^2 Effect of Envelope Conductance and Infiltration

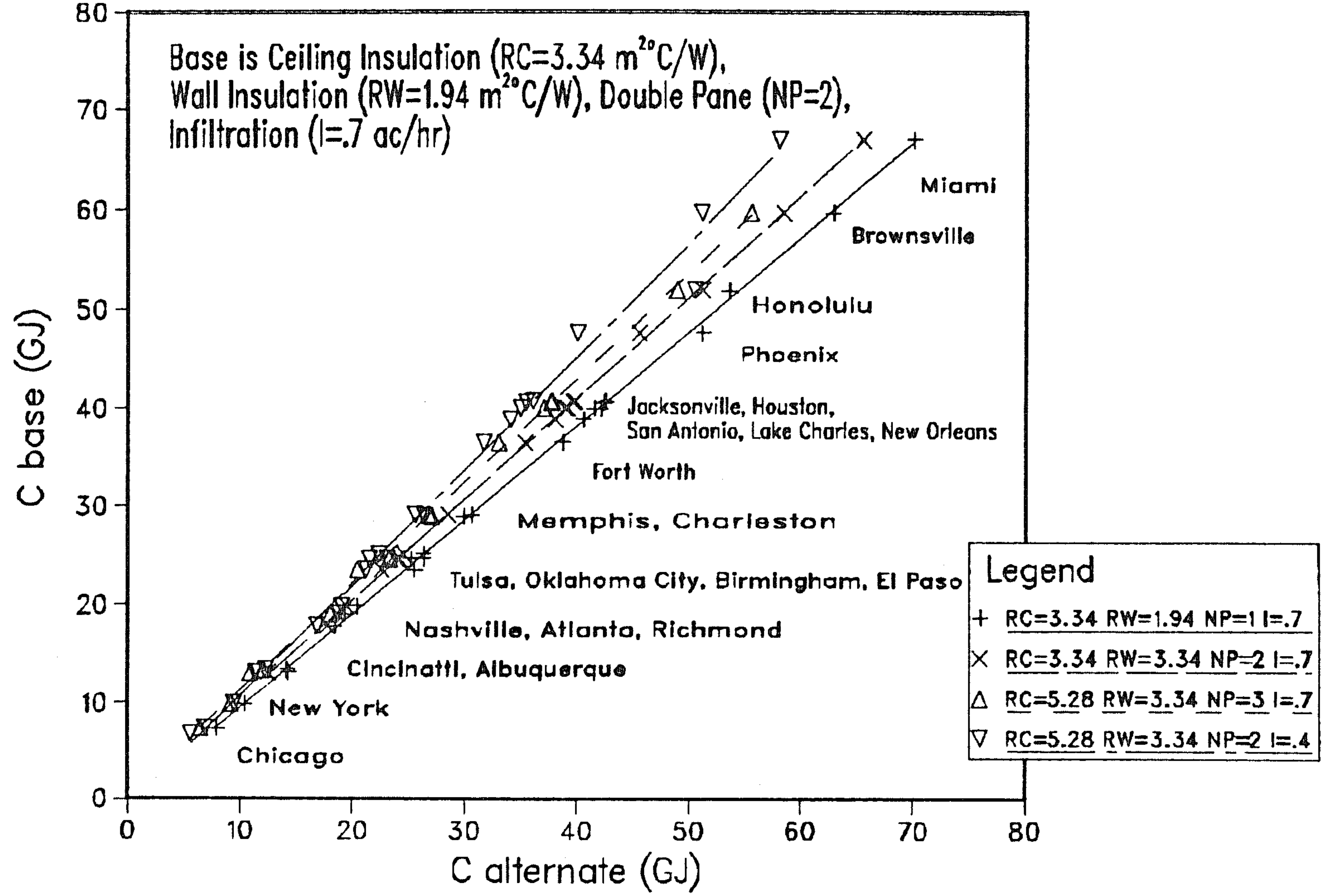

FIGURE 3 Residential Heating Load Comparison for Various Configurations and Geographic Locations(TMY) Using BLAST, Ranch Style House, Slab-on-Grade, Four Zone 111.5 m²
Effect of Envelope Mass Properties

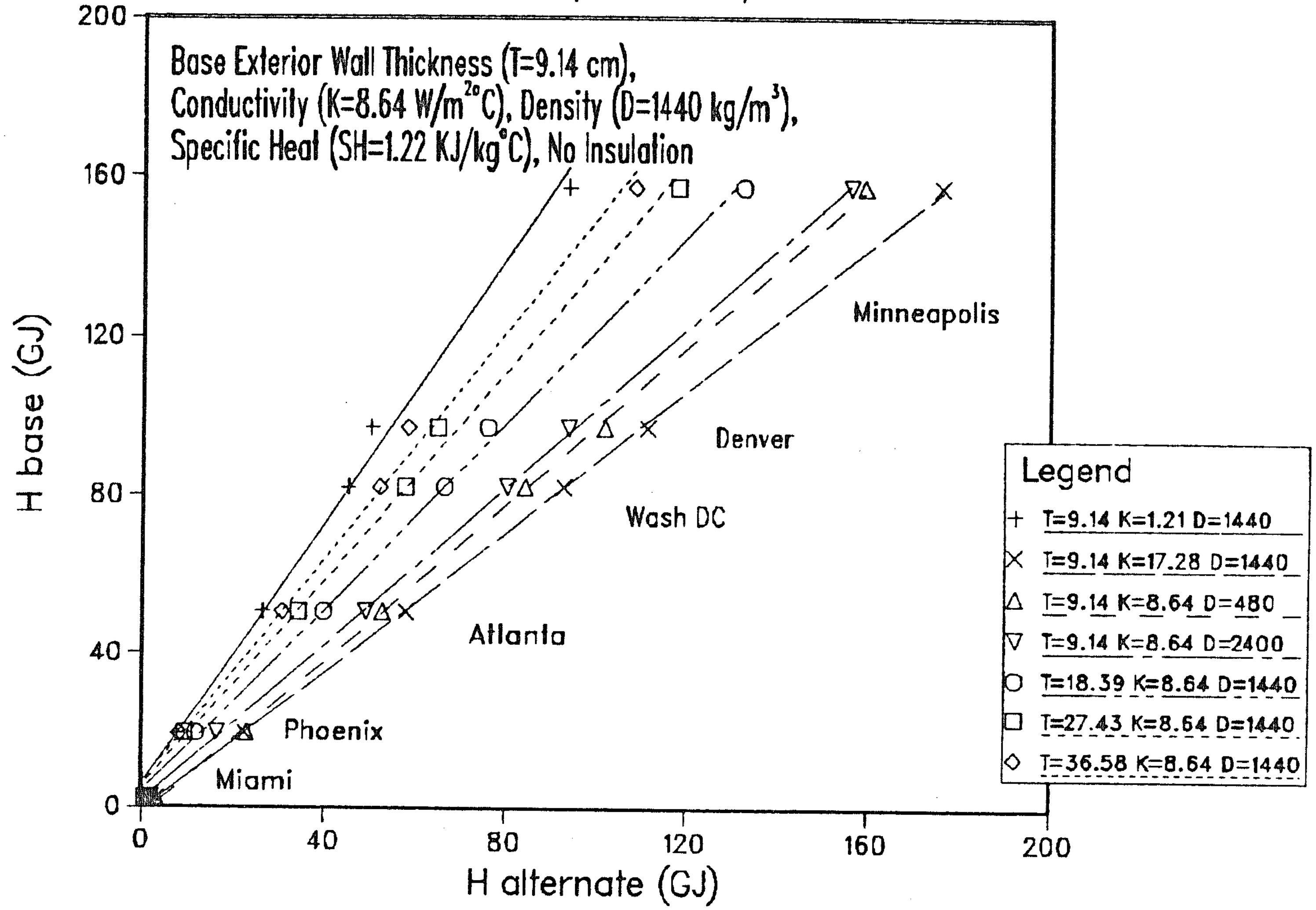

FIGURE 4 Residential Cooling Load Comparison for Various Configurations and Geographic Locations(TMY) Using BLAST, Ranch Style House, Slab–on–Grade, Four Zone 111.5 m^2 Effect of Envelope Mass Properties

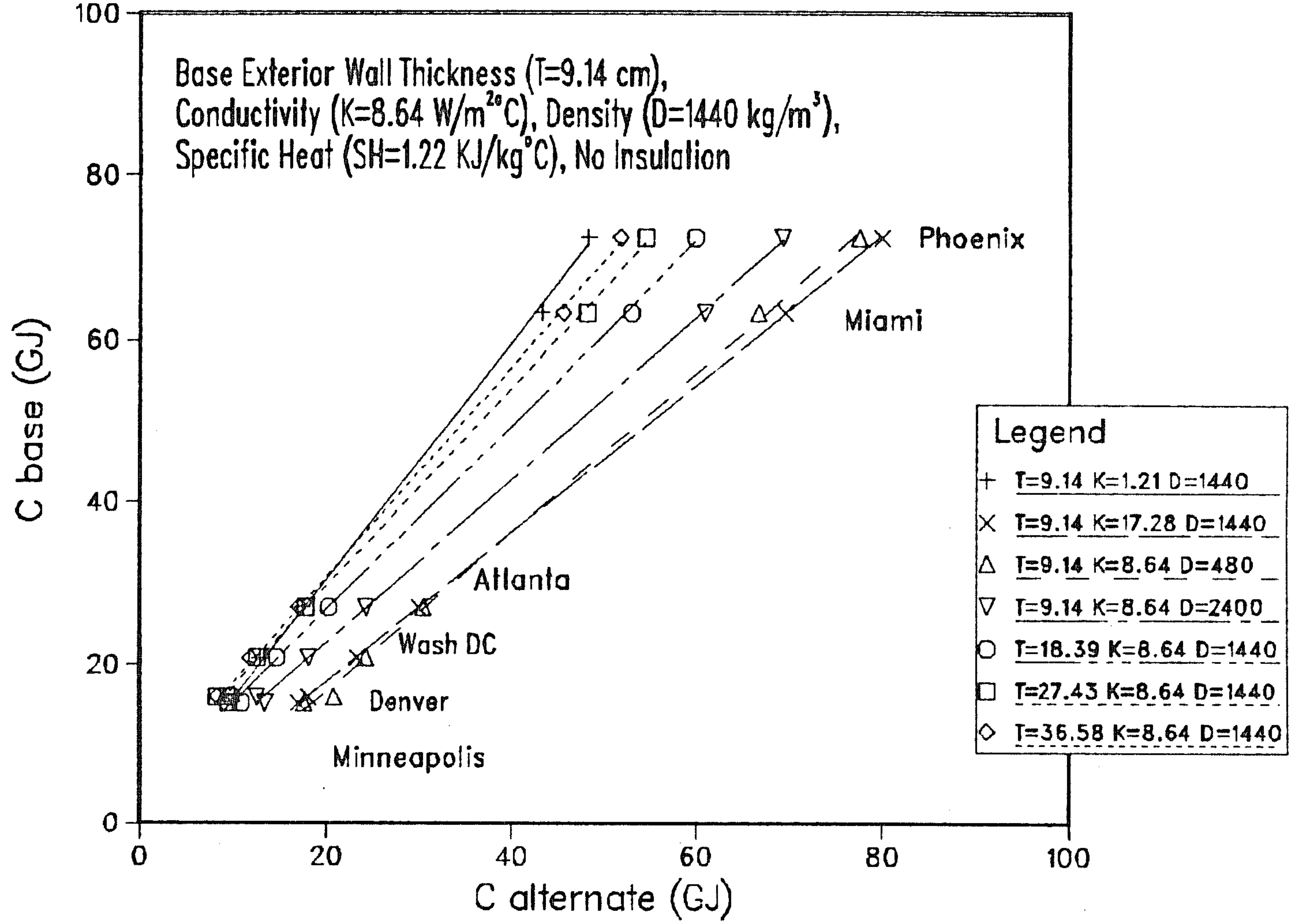

FIGURE 5 Residential Heating Load Comparison for Various Configurations and Geographic Locations(TMY) Using BLAST, Ranch Style House, Slab–on–Grade, Four Zone 111.5 m^2 Effect of Envelope Mass, Thermostat Setpoints, Night Setback

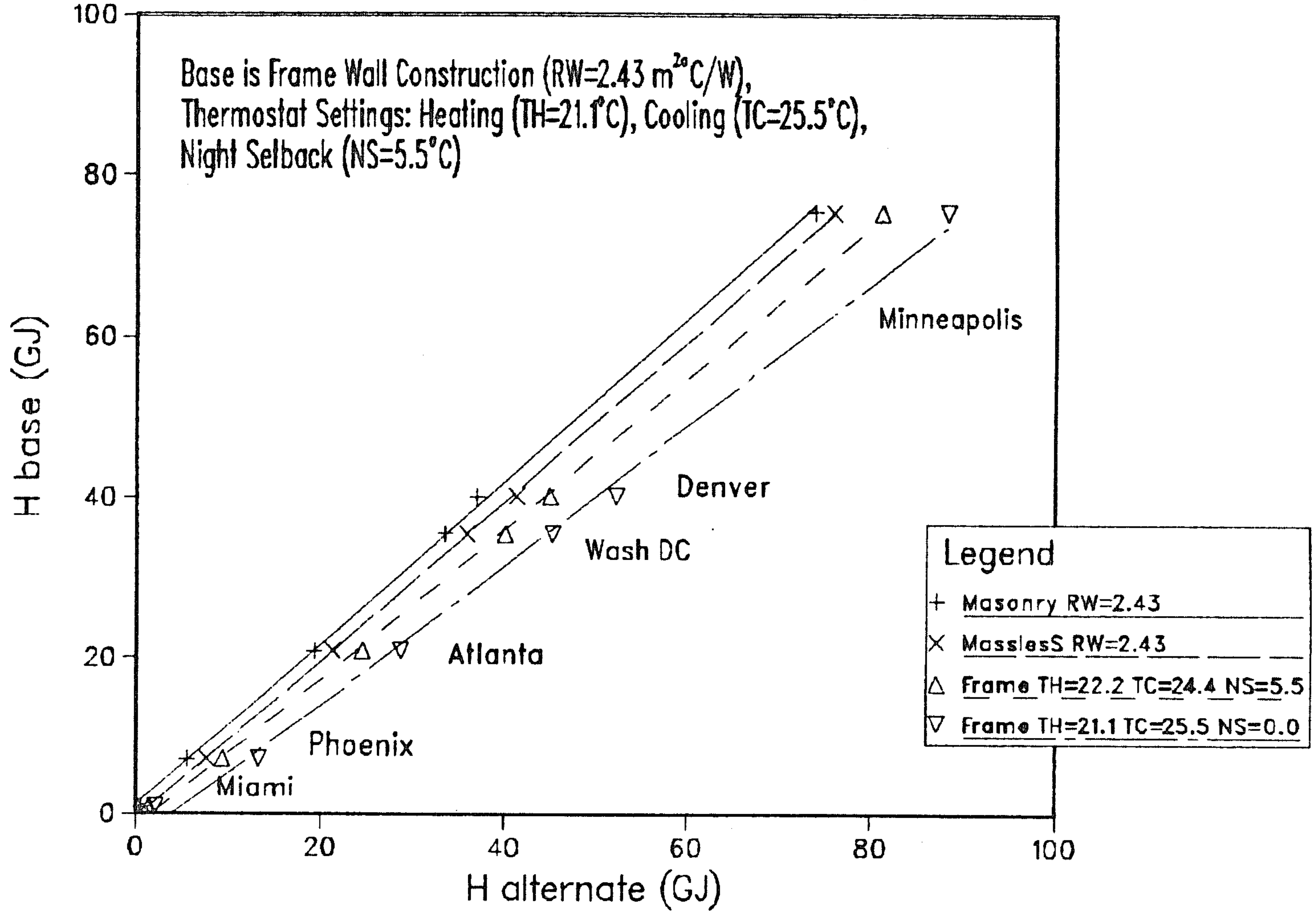

FIGURE 6 Residential Cooling Load Comparison for Various Configurations and Geographic Locations(TMY) Using BLAST, Ranch Style House, Slab-on-Grade, Four Zone 111.5 m^2 Effect of Envelope Mass, Thermostat Setpoints, Night Setback

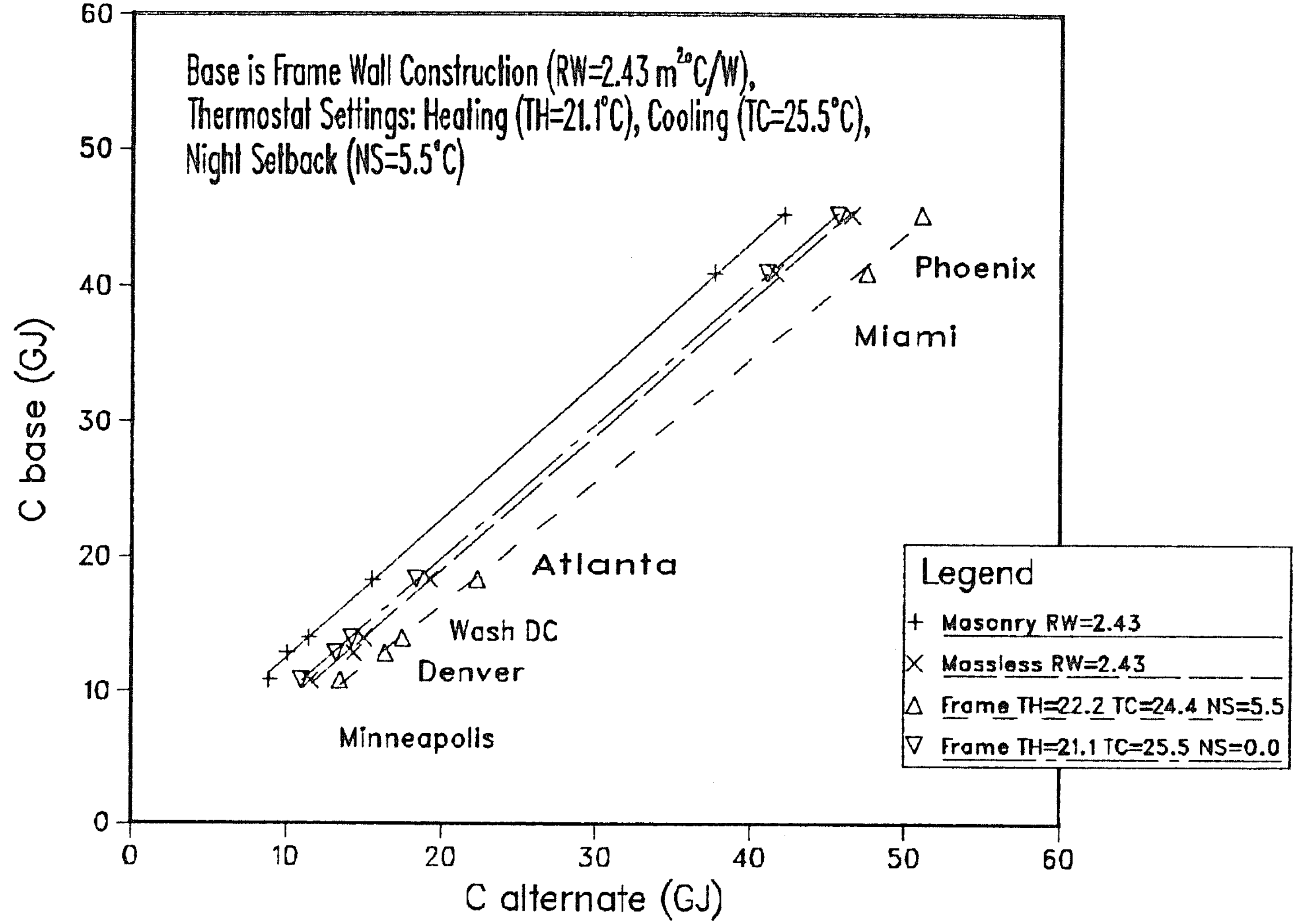

FIGURE 7 Residential Heating Energy Comparison for Various Configurations and Geographic Locations(WYEC) Using DOE-2.1B, Ranch Style House, Slab-on-Grade, One Zone 143 m^2
Effect of Window Parameters

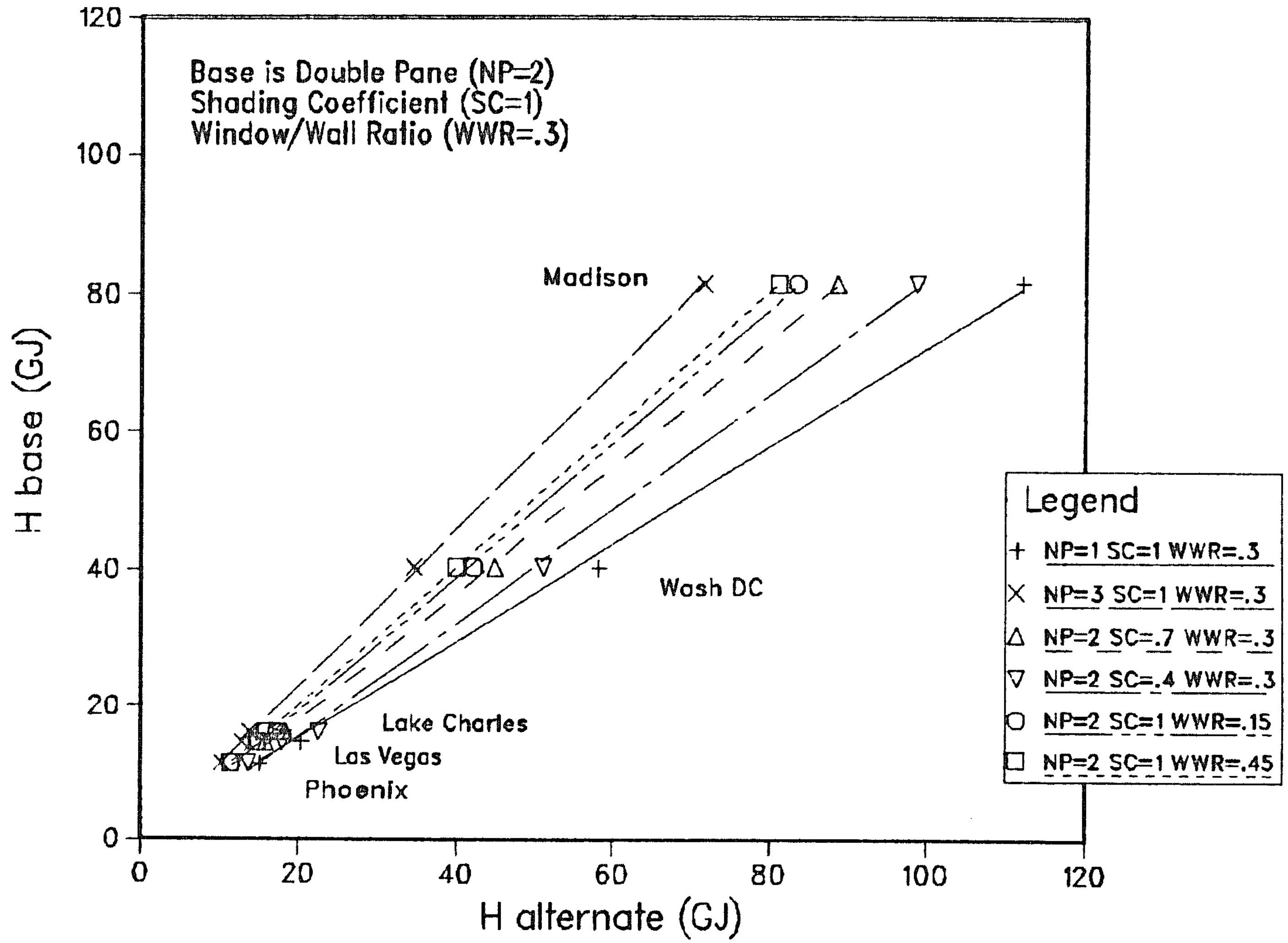

FIGURE 8 Residential Cooling Energy Comparison for Various Configurations and Geographic Locations(WYEC) Using DOE-2.1B, Ranch Style House, Slab-on-Grade, One Zone 143 m^2 Effect of Window Parameters

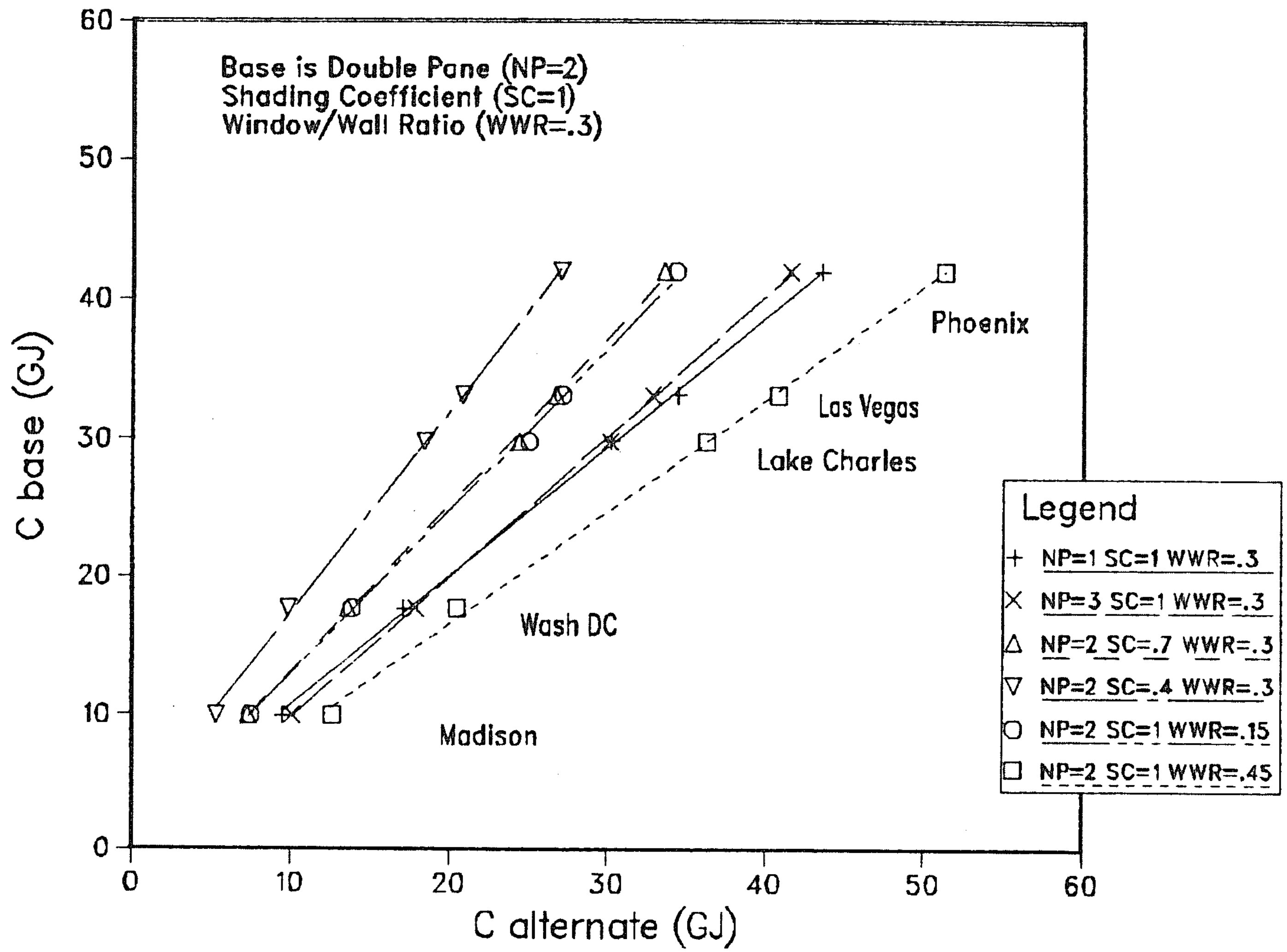

FIGURE 9 Residential Heating Load Comparison for Various Configurations and Geographic Locations(TRY) Using DOE–2.1A, Multi–Family Apartment, Slab–on–Grade, Six Units 111.5 m^2, End Unit Average, Effect of Envelope Conductance and Infitration

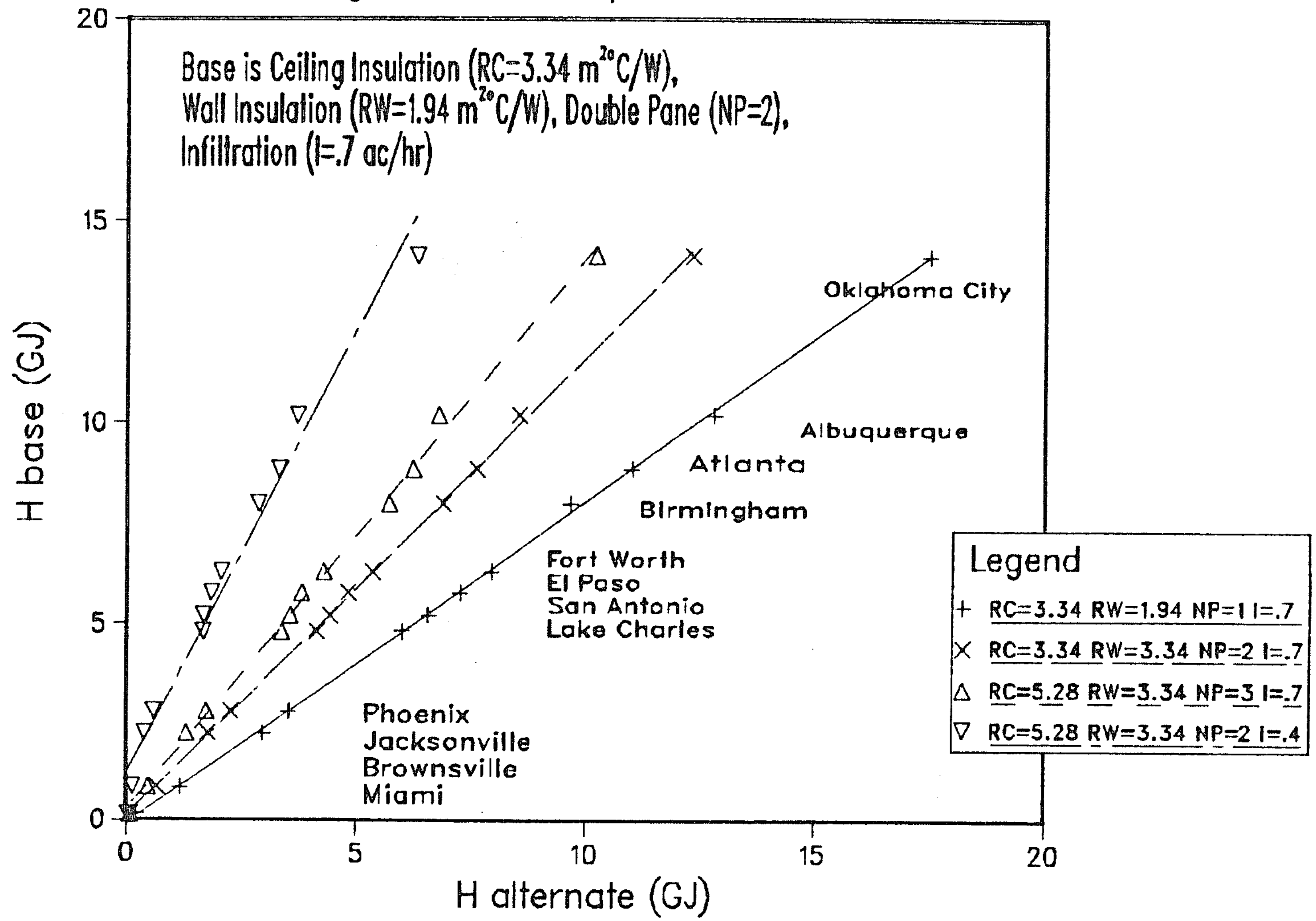

FIGURE 10 Residential Cooling Load Comparison for Various Configurations and Geographic Locations(TRY) Using DOE–2.1A, Multi–Family Apartment, Slab–on–Grade, Six Units 111.5 m^2 End Unit Average, Effect of Envelope Conductance and Infiltration

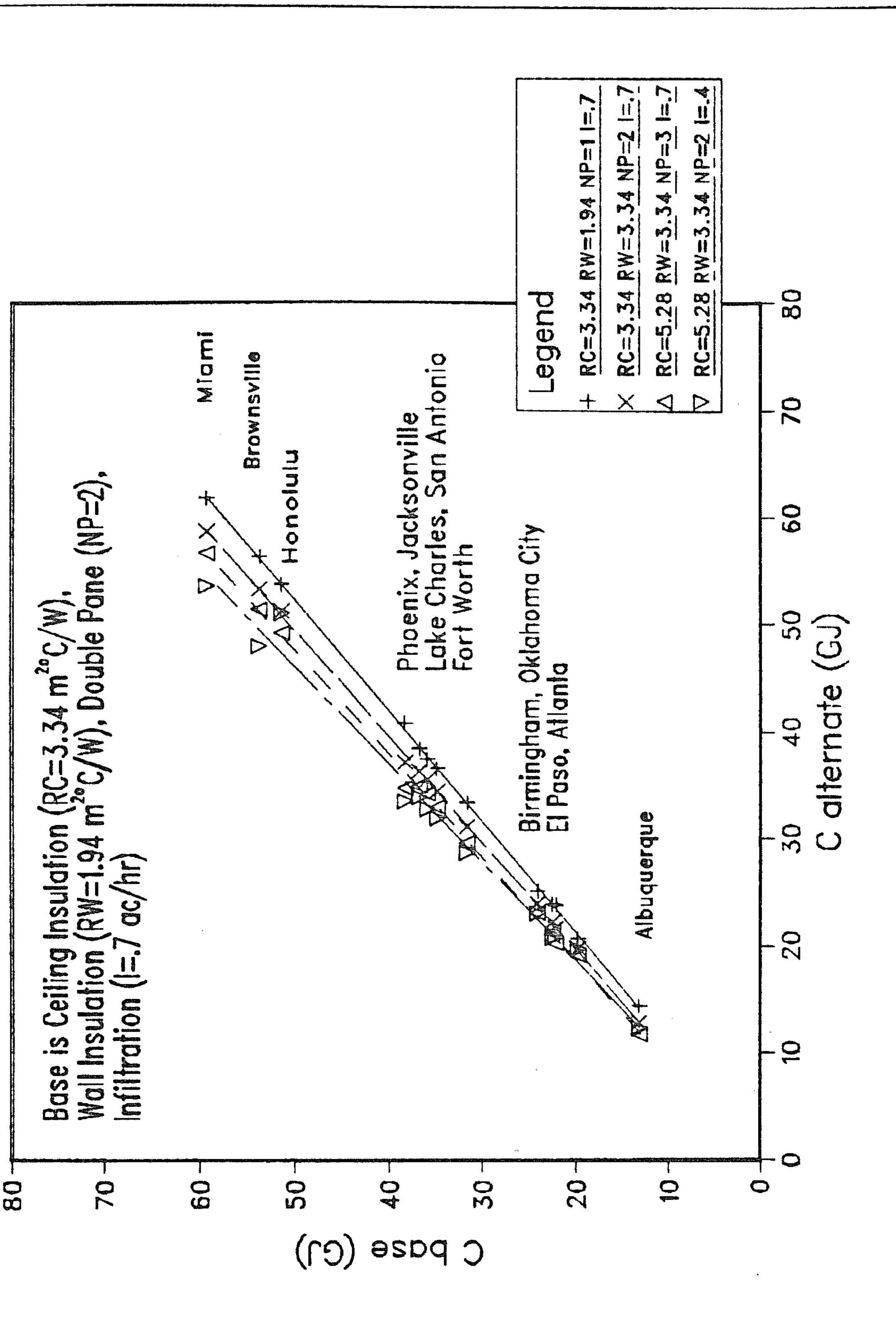

FIGURE 11 Residential Heating Load Comparison for Various Configurations and Geographic Locations, Presentation for Use as a Developmental Tool